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Oxygen model

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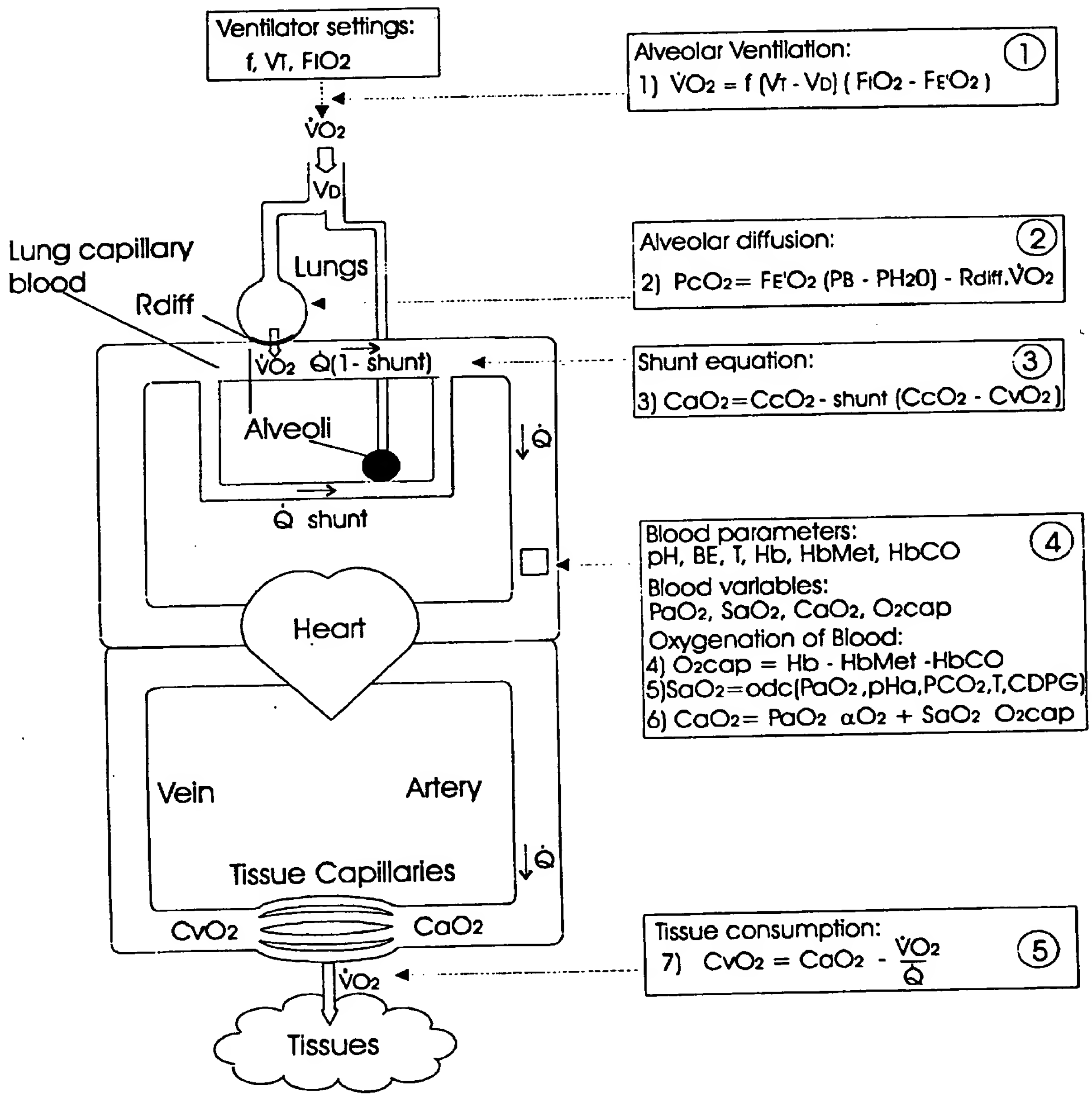
The oxygen model

The model illustrated in the figure represents the transport of oxygen from the inspired air to the tissues. Oxygen enters the body via gases breathed into the lungs. The lungs are in contact with a network of small veins known as the lung capillaries which receive blood pumped directly from the heart. Oxygen is transported into the blood stream by diffusion from the lungs into the lung capillary blood. This blood is then pumped by the heart through the arteries of the body, before reaching a network of small veins passing through the tissues known as tissue capillaries. On reaching the tissue capillaries oxygen diffuses from the blood into the tissues. The deoxygenated blood returns to the heart via the veins and is once again pumped through the lung capillaries. The mathematical model describing the transport of oxygen from the lungs to the tissues illustrated in the figure includes 7 equations, each of which is now described in detail.



Equation 1 describes the flow of oxygen into the blood from the alveoli ($\dot{V}O_2$). The volume of air flowing into the lungs per breath is known as the tidal volume (V_T). Before reaching the lower part of the lungs (i.e. the alveoli) this gas passes through a region which is not involved in exchanging gases with the blood. This region is known as the dead space and contains a volume of gas V_D. The volume of gas reaching the alveoli per breath is therefore $V_T - V_D$. If the volume of gas reaching the alveoli per breath is multiplied by the number of breaths per minute, known as the respiratory frequency (f), the total volume of gas reaching the alveoli per minute can be calculated.

The flow of oxygen into the blood from the alveoli per minute ($\dot{V}O_2$) can then be calculated as the product of the volume of gas flowing into the alveoli per minute $f\ (V_T - V_D)$ and the difference between the fraction of oxygen in the inspired F_IO_2 and expired gas $F_{E'}O_2$, as described in equation 1.

$$\dot{V}O_2 = f\ (V_T - V_D)\ (F_IO_2 - F_{E'}O_2) \qquad (1)$$

Equation 2 describes the partial pressure of oxygen in lung capillary blood (PcO_2). This equation is derived from the definition of resistance, i.e.

$$\text{Resistance} = \frac{\text{Pressure difference}}{\text{Flow}}$$

This equation can be written to describe the resistance to diffusion of oxygen from alveoli to lung capillary blood (Rdiff) i.e.

$$\text{Rdiff} = \frac{P_AO_2 - PcO_2}{\dot{V}O_2}$$

where P_AO_2 is the pressure of oxygen in the alveoli, PcO_2 is the pressure of oxygen in the lung capillary blood, and $\dot{V}O_2$ is the flow of oxygen from the alveoli to the lung capillary blood.

The pressure of oxygen in the alveoli (P_AO_2) can be converted into the fraction of oxygen ($F_{E'}O_2$) in the alveoli using the following equation $P_AO_2 = F_{E'}O_2(P_B - P_{H20})$, where P_B is the barometric pressure and P_{H2O} is the pressure of water in the gases of the lungs. By replacing P_AO_2 with $F_{E'}O_2(P_B - P_{H20})$ in the above equation and rearranging this equation we obtain equation 2 i.e.

$$PcO_2 = F_{E'}O_2\ (P_B - P_{H20}) - \text{Rdiff}\ \dot{V}O_2 \qquad (2)$$

Equation 3 describes the concentration of oxygen in the arterial blood (CaO_2). The total volume of blood flowing through the heart and lungs per minute is known as the cardiac output ($\dot{Q}$). As this blood flows through the lungs a fraction of it passes alveoli which receive no inspired gases. As a consequence the blood does not become oxygenated and has the same oxygen concentration as blood in the veins (CvO_2). This fraction of blood is known as the shunt fraction (shunt). Blood flowing out of the lung capillaries mixes with the shunted blood before being pumped into the arteries by the heart. Equation 3 describes this mixing and the resultant concentration of oxygen in

the arterial blood, and is derived as follows

The total flow of blood through the lungs ($\dot{Q}$) is the sum of that flowing via the shunt pathway ($\dot{Q}$ shunt) and that flowing through lung capillaries containing inspired gases ($\dot{Q}$ (1-shunt)), i.e.

$$\dot{Q} = \dot{Q}\,\text{shunt} + \dot{Q}\,(1\text{-shunt})$$

In a similar way the flow of oxygen into the arteries ($\dot{Q}$ CaO2) is the sum of that from the shunt pathway ($\dot{Q}$ shunt CvO2) and that coming from lung capillaries ($\dot{Q}$ (1-shunt) CcO2), i.e.

$$\dot{Q}\,\text{CaO2} = \dot{Q}\,\text{shunt CvO2} + \dot{Q}\,(1\text{-shunt})\,\text{CcO2}$$

By rearranging this equation we obtain equation 3 describing the concentration of oxygen in the arterial blood (CaO2), i.e.

$$\text{CaO2} = \text{CcO2} - \text{shunt}\,(\text{CcO2} - \text{CaO2}) \qquad (3)$$

Equations 4, 5 and 6 describe the transport of oxygen in the arterial blood. The majority of oxygen in the blood is bound to Haemoglobin (Hb). Haemoglobin can also bind other gases reducing its capacity to bind oxygen. In particular haemoglobin may be bound to other gases forming carboxy-haemoglobin (HbCO) and methyl-haemoglobin (HbMet).

Equation 4 describes the oxygen capacity of the haemoglobin (O_2cap), and is written as

$$O_2\text{cap} = \text{Hb} - \text{HbMet} - \text{HbCO} \qquad (4)$$

where Hb is the effective haemoglobin concentration and HbMet and HbCO are the concentration of haemoglobin bound to other gases.

The binding of oxygen to haemoglobin is a chemical reaction. At high oxygen pressure (PaO2) in the blood all available haemoglobin will bind oxygen. In this case the haemoglobin is fully saturated with oxygen. At lower PaO2 values some of the haemoglobin will not bind oxygen and the haemoglobin is no longer fully saturated. The haemoglobin oxygen saturation (SaO2) varies not only with the oxygen pressure in the blood but also with a number of other variables which modify the chemical reaction. These include the acidity of the blood (pHa), the pressure of carbon dioxide (PCO2), the temperature of the blood (T) and the concentration of 2,3-Diphosphoglycerate (CDPG). The relationship between the haemoglobin oxygen saturation and these variables is described by a function known as the oxygen dissociation curve (odc), implemented as part of this model and represented in equation 5.

$$\text{SaO2} = \text{odc}\,(\text{PaO2}, \text{pHa}, \text{PCO2}, \text{T}, \text{CDPG}) \qquad (5)$$

Mathematical functions representing the odc are available in the literature. Our model uses that published by Siggaard-Andersen (1). The concentration of oxygen bound to haemoglobin can then be calculated as the haemoglobin oxygen saturation multiplied by the oxygen capacity of haemoglobin (SaO2 O_2cap)

Whilst the majority of oxygen in the blood is bound to haemoglobin some is dissolved in the blood. The concentration of dissolved oxygen is the product of the oxygen pressure (PaO2) and the solubility coefficient for oxygen in blood ($\alpha O2$). The total concentration of oxygen in the blood (CaO2) is then the sum of that dissolved and that bound to haemoglobin, as described by equation 6, i.e.

$$CaO2 = PaO2\ \alpha O2 + SaO2\ O_2cap \qquad (6)$$

Equation 7 describes the concentration of oxygen in the venous blood (CvO2) and is derived as follows. The mass of oxygen flowing into the tissue capillaries from the arteries must equal that flowing out of the tissue capillaries, this relationship can be expressed as follows

The mass of oxygen flowing from the arteries to the tissue capillaries	=	The mass of oxygen flowing from the tissue capillaries to the veins	+	The mass of oxygen flowing from the tissue capillaries to the tissues

This expression can be represented mathematically as

$$CaO2\ \dot{Q} = CvO2\ \dot{Q} + \dot{V}O2$$

This equation can be rearranged to give equation 7

$$CvO2 = CaO2 - \frac{\dot{V}O2}{\dot{Q}} \qquad (7)$$

Reference

1) Siggaard-Andersen O, PD Wimberley, I Gøthgen, M Siggaard-Andersen (1984) - A mathematical model of the hemoglobin-oxygen dissociation curve of human blood and of the oxygen partial pressure as a function of temperature. Clin Chem, vol. 30, pp 1646-51.